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Preliminary requirements for the design of the PS2 main magnets

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Abstract

The aim of this note is to give preliminary requirements for the PS2 main magnets as input for a first design and cost estimate. The aperture requirements are based on PS2 lattice studies that are presently ongoing and therefore changes may occur when the study progresses. Tight requirements are quoted for the field quality, these will have to be refined by dynamic aperture and tracking studies at a later stage. The anticipated machine cycles for the most important operations are quoted and typical operation scenarios are discussed as input for powering requirements. It is assumed that the machine will have a classical vacuum system without bake-out equipment in the magnets.

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Lattice functions

Based on the ongoing analysis of different cell structures for the arcs, the following upper limits for the lattice functions are assumed:

	$\mathrm{Beta}_{hor.max.}$ [m]	$\mathrm{Beta}_{vert.max.}$ [m]	$\mathrm{Dispersion}_{hor.max.}$ [m]
Dipoles	40	40	5.0
Quadrupoles	60	60	6.0

Table 1: Assumed maximum lattice functions in PS2.

Reference beam parameters

The largest beam that will have to be provided by the PS2 machine is a high-intensity beam for fixed target physics, comparable to the present SPS fixed target beam. It is assumed that the future high-intensity beam will have the same normalized transverse emittances as the present fixed target beam. Normalized and geometrical emittances at injection energy of 3.5 GeV and extraction energy of 50 GeV are quoted below.

	$\varepsilon_{\sigma,norm.}$ [μm]	$\varepsilon_{\sigma,geom,\ 3.5GeV}$ [μm]	$\varepsilon_{\sigma,geom,\ 50GeV}$ [μm]
Horizontal plane	15.0	3.3	0.28
Vertical plane	8.0	1.8	0.15

Table 2: Transverse emittances for high intensity fixed target beam in PS2 - upper limits.

The longitudinal emittance at injection is not yet defined nor is the voltage program at the low-energy part of the acceleration cycle. A typical value for the sigma momentum spread of $\Delta p/p = 1\cdot 10^{-3}$ at injection is assumed.

Maximum beam sizes

The horizontal and vertical beam half-envelopes are calculated from the above parameters by quadratic addition of the contributions from emittances and momentum spread according to

$$\sigma = \sqrt{\varepsilon \cdot \beta + \left(D \cdot \frac{\Delta p}{p} \right)^2} \ .$$

The 3-sigma envelopes are assumed to contain 100% of the beam and are used for the aperture determination. Table 3 lists the 3-sigma maximum half-beam sizes at injection in dipoles and quadrupoles.

INJECTION 3.5 GeV	Max. hor. ½ beam size [mm]	Max. vert. ½ beam size [mm]
Dipoles	37.6	25.5
Quadrupoles	45.9	31.2

Table 3: Maximum half beam sizes (3σ) at injection in bending and quadrupole magnets.

Table 4 summarizes the beam sizes at extraction energy. There is a significant difference between horizontal and vertical planes. In the vertical plane the beam size shrinks due to adiabatic damping. The situation is different in the horizontal plane because of the slow resonant extraction and the multi-turn island extraction. The space required for separatrices or islands is assumed to be identical to the horizontal beam size at injection.

EXTRACTION 50 GeV	Max. hor. ½ beam size [mm]	Max. vert. ½ beam size [mm]
Dipoles	37.6	7.4
Quadrupoles	45.9	9.0

Table 4: Maximum half beam sizes (3σ) at extraction in bending and quadrupole magnets.

Closed orbit

For both planes and at all energies maximum closed orbit distortions of 5 mm at the maximum beta-functions are assumed. The maximum closed orbit scales with the square-root of the beta-functions around the machine.

Good field region

The good field region is defined by the maximum beam sizes and the closed orbit margins. Tables 5 and 6 summarize the good-field regions (with respect to the central orbit) for dipoles and quadrupoles at injection and extraction.

INJECTION 3.5 GeV	Good field region hor. [mm]	Good field region ver. [mm]
Dipoles	± 41.7	± 29.6
Quadrupoles	± 50.9	± 36.2

Table 5: Good field regions at injection in dipole and quadrupole magnets.

EXTRACTION 50 GeV	Good field region hor. [mm]	Good field region ver. [mm]
Dipoles	± 41.7	± 11.5
Quadrupoles	± 50.9	± 14.0

Table 6: Good field regions at extraction in dipole and quadrupole magnets.

Magnet aperture requirements

Dipole magnets:

The dipole gap height is determined by the beam size at injection. The vertical good field region is 29.6 mm and another 5 mm are added to account for vacuum chamber and alignment. This results in a half gap height of 34.6 mm. *Therefore a total gap height of 70 mm seems adequate for the main bending magnets.* The gap width is estimated to around 3 times the gap height, 20 to 25 cm.

Quadrupole magnets:

The quadrupole aperture (pole radius) is determined by the horizontal beam size at injection and extraction. The required good field region is ± 50.9 mm and adding 10 mm for chamber and alignment defines the minimum pole radius at ~61 mm. However it is assumed that the good field region extends to about 70% of the pole radius. *Therefore a pole radius of 75 mm seems adequate for the main quadrupole magnets.*

Field range

The injection energy of the PS2 for proton operation is 3.5 GeV and the maximum extraction energy is 50 GeV. The corresponding magnet rigidities are $B\rho_{3.5GeV}$ = 14.5 Tm and $B\rho_{50GeV}$ = 170 Tm.
For the bending magnets a maximum field of 1.8 T is assumed. Scaling with the magnetic rigidities sets the injection field to 0.15 T.

For the quadrupole magnets a maximum gradient of 16 T/m is assumed (giving a pole tip field of 1.2 T with 75 mm pole radius). Scaling with the magnetic rigidities results in a gradient of 1.35 T/m at injection. A reduction by 30% is added to ensure a large tuning range so that the main quadrupoles have a working range from 0.95 T/m to 16 T/m.

Number and lengths of magnets

The machine lattice and therefore the exact geometry are not yet fixed. For the main bending magnets it is assumed that there will be 200 units of 3 m length each. For the main quadrupole magnets it is assumed that there will be 120 units of 1.75 m length each.

Field quality requirements

The exact specifications for the field quality will require detailed tracking studies. For the time being the requirements for the field (gradient) homogeneity inside the good-field regions are $\pm 1\cdot 10^{-4}$ for the dipole magnets and $\pm 3\cdot 10^{-4}$ for the quadrupole magnets.

Summary on magnet parameters and requirements

The main parameters for the main magnets are summarized in Table 7.

PS2 main magnets		
Number of dipoles		200
Dipole field at ejection	[T]	1.8
Dipole field at injection	[T]	0.15
Magnetic length	[m]	2.965
Bending angle	[mrad]	31.416
Number of quadrupoles		120
Maximum gradient	[T/m]	16
Minimum gradient	[T/m]	0.95
Magnetic length	[m]	1.75

Table 7: PS2 main magnet parameters.

Working range, good field regions and field qualities are summarized for dipoles in Table 8 and for the quadrupoles in Table 9.

Dipoles	B_{nom} [T]	Br [Tm]	good field hor. [mm]	good field ver. [mm]	$\frac{(B-B_{nom})}{B_{nom}}$	gap [mm]
Injection	0.15	14.5	± 41.7	± 29.6	$\pm 1\cdot 10^{-4}$	70
Extraction	1.80	170.0	± 41.7	± 11.5	$\pm 1\cdot 10^{-4}$	

Table 8: Dipole working range and field quality requirements.

Quadrupoles	G_{nom} [T/m]	Br [Tm]	good field hor. [mm]	good field ver. [mm]	$\frac{(G-G_{nom})}{G_{nom}}$	pole [mm]
Injection	1.35 (0.95)	14.5	± 50.9	± 36.2	$\pm 3\cdot 10^{-4}$	75
Extraction	16.0 (11.2)	170.0	± 50.9	± 14.0	$\pm 3\cdot 10^{-4}$	

Table 9: Quadrupole working range and gradient quality requirements.

It should be noted that the working ranges are valid for proton operation. The different options for PS2 ion operation are being analyzed separately. In the case of injection directly from LEIR the ion beam magnetic rigidity would be 6.7 Tm, equivalent to 1.3 GeV protons, corresponding to a PS2 dipole bending field of only 0.07 T and a minimum quadrupole gradient of 0.44 T/m.

PS2 machine cycles

The PS2 will provide many different beams to various users. This implies that there will be different cycles. The length of all cycles will also depend on the injector upgrade. The injection plateau will be shortest (and the repetition rate the highest) with the SPL as injector and therefore this case is used to estimate the rms power. The maximum ramp-up and ramp-down rates are assumed to be ± 1.5 T/s.
A simplified cycle for LHC and CNGS type beams for the SPS consists of a 100 ms injection plateau, a linear ramp-up at 1.5 T/s, a 100 ms extraction plateau and a ramp-down at -1.5 T/s. Each ramp takes 1100 ms so that the overall cycle length is 2400 ms as shown in Figure 1.

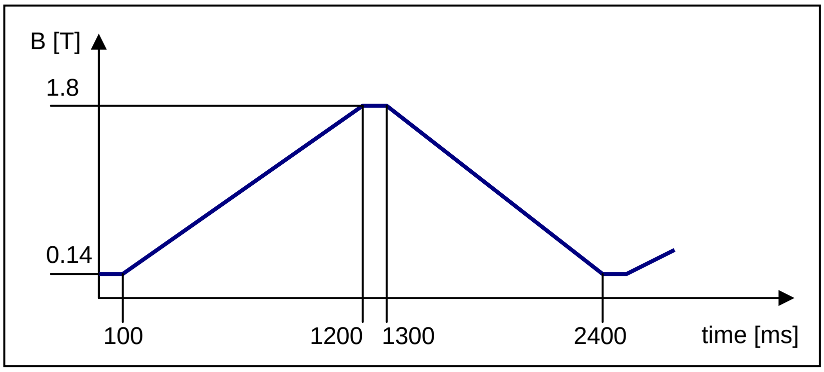

Figure 1: Simplified PS2 magnetic cycle for LHC and CNGS type beams.

The cycle for slow extraction from the PS2 will have identical injection and ramps but the extraction plateau at 50 GeV will be 1.3 s long giving a total duration of 3.6 s as shown in Figure 2.
For the estimation of rms currents and rms power a super-cycle built from the above two cycles (alternating always 2.4 s and 3.6 s cycles) should be used.

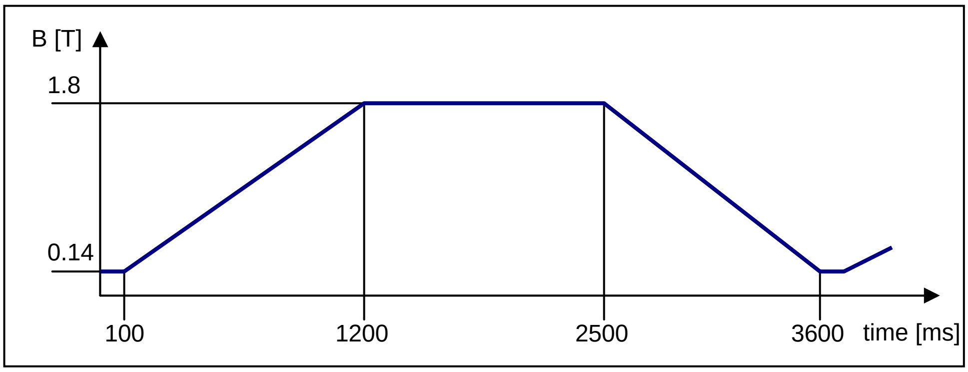

Figure 2: Simplified PS2 magnetic cycle for slow extraction.

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